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Comparison of Two Methods for the Assessment of Chloride Ion Penetration in Concrete: A Field Study

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To the Graduate Council:

I am submitting herewith a thesis written by Eric William Ryan entitled "Comparison of Two Methods for the Assessment of Chloride Ion Penetration in Concrete: A Field Study." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

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Comparison of Two Methods for the Assessment of Chloride Ion Penetration in Concrete: A Field Study

A thesis presented for the

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Eric William Ryan

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Dedication

I dedicate my work to my mother, most of all, who has given me the inspiration, guidance, support, and love to make virtually anything possible. She is the true definition of Sisu. I also dedicate my work to my grandparents who taught me that learning and education are never ending. They are the standards I try to live my life by every day.

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I would be remiss not to give a big thanks to my partner Brian Buchanan for all his work and dedication to the project (and his seemingly flexible schedule!). His determination and spirit always inspires me.

Last, but certainly not least, I want to thank my ever supportive family, especially my mother. In addition, I would like to thank my teammates, roommates, and Coach Watts for their support, continued understanding, and for giving me the opportunity to pursue my athletic AND academic goals.

Abstract

The currently accepted method for assessing the resistance of concrete to penetration of chloride ions is ASTM C1202, commonly known as the "Rapid Chloride Permeability (RCP) Test." The test is time-consuming, laborious, has rather high variability, and, is to a degree, user sensitive, making it problematic for inclusion in a performance-based specification. A potential alternative to the RCP test is the "Surface Resistivity (SR) Test", a method which is dramatically easier, faster, and has less variability than the RCP test. The research reported herein was directed toward determining a correlation between RCP and SR test measurements for Tennessee bridge deck concrete, based on cylinders collected from concrete bridge decks being constructed across the state, and evaluating the appropriateness of the SR test as an alternative to the RCP test for inclusion in a performance-based specification. Results of the testing showed a clear correlation between the two methods and identified potential limits for possible inclusion in a performance-based specification.

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1 Introduction

As construction projects become ever larger, more costly, and more complex, it has become even more important for structures to be reliable, cost effective, and long-lasting. In response, much of current bridge related research seeks ways to evaluate and improve the current protocols for bridge design to reduce maintenance and repair costs.

One way to potentially improve the reliability and life span of bridges and mitigate repair costs would be the implementation of a performance based specification for concrete placed in bridge decks. In Tennessee, a Class D concrete mix is specified for all public bridge construction projects. This prescriptive specification gives limits and guidelines for concrete mix design proportions as well as compressive strength minimums; however, it fails to specify any performance based criterion to assess durability. In fact, the strength and mix design limits can be met without necessarily producing desirable, long lasting concrete worthy of public bridges. If, instead, a performance based specification were implemented, the durability of the concrete could be addressed by specifying appropriate ranges on certain durability measures such as shrinkage or chloride ion penetrability. These types of measurements are indeed possible and could be included in a specification; however, current protocols for measuring these criteria are not practical in the field because of the length of the tests or their sensitive, laborious nature. For example, one can argue that shrinkage is, perhaps, the best measure of durability. However, the inclusion of a shrinkage limit in a performance based specification is problematic considering its labor intensive measurements. To be effective and practical, a durability measurement criterion should be *both* an appropriate representation of durability and easily measured, with confidence, in a short time frame.

One of the primary concerns in concrete durability assessment is corrosion risk due to the penetration of chloride into concrete. ACI committee 201 reports: “the permeability of concrete to water and chloride is the major factor affecting the process of corrosion of embedded metals” (p.19). Once chloride ions have penetrated through the concrete, the steel surface can oxidize,

compromising the bond that exists between the concrete and steel reinforcement. The oxidation causes the characteristic spalling which is so often responsible for the rapid deterioration of bridge decks and leads to expensive repairs. In addition, the ingress of the chloride ions into concrete can produce excessive cracking. As cracks form, the concrete subsurface becomes more exposed and susceptible to further chloride ion penetration and, in turn, more steel degradation and further cracking. In relation to shrinkage, it turns out that the same concrete mixture variables that lead to lower chloride ion penetration also lead to lower shrinkage. Thus, chloride ion penetration turns out to be an appropriate measure of durability, but the question is whether it can be quickly measured with confidence.

The currently accepted measurement of chloride ion penetrability and permeability in concrete is referred to as the "Rapid Chloride Ion Penetration (RCP) Test" as detailed in ASTM C1202 and AASHTO T 277. In the test, a constant voltage is applied across a concrete specimen, and the amount of charge that passes through the specimen in a 6-hour period is measured. A full 24-hour preparation period is required before this 6-hour test can occur. So, while chloride ion penetration can be measured, the test is laborious, time consuming, somewhat user dependent, and has a high coefficient of variation, thus making it impractical to include in any performance-based specification.

Another measure, surface resistivity, has been proposed by several research studies and DOTs as an alternative to the RCP test as an indicator of chloride ion penetration. In fact, an AASHTO specification is currently being written and tested by members of the Florida Department of Transportation (FDOT) for the use of surface resistivity measurements as an indicator of chloride ion penetration. The test consists of placing a hand-held probe onto the surface of the concrete specimen and recording the resistivity of the concrete. The test is both quick and easy and requires no sample preparation, making it more appropriate for a performance based specification. In preliminary studies conducted here at the University of Tennessee by Andrew Tinsley in his M.S. thesis research, surface resistivity showed good correlation with the RCP test and had less variability on lab produced samples, but more samples and data were needed to

make significant conclusions. The current research project sponsored by the Tennessee Department of Transportation (TDOT) is directed toward obtaining a large amount of data, not from lab samples but from actual job sites, and determining a valid correlation.

The objectives of this research project are to evaluate the use of surface resistivity measurement using an SR meter as an appropriate alternative to the Rapid Chloride Ion Penetration (RCP) test as an effective durability measurement for use in a performance based specification in Tennessee. To accomplish this objective, concrete samples were to be collected from actual bridge deck pours across the state of Tennessee over a two-year period and tested using both the RCP test and the SR meter to evaluate the correlation between the two measurements as well as the appropriateness of using surface resistivity as a measure of durability. Also, appropriate limits of RCP values and SR values are to be established for use in a performance-based specification.

2 Literature Review

The function of this chapter is to highlight the mechanisms, influencing factors, and test methods for both chloride ion penetration and surface resistivity of concrete as reported in current literature.

2.1 Mechanisms of Chloride Ion Penetration

The main ways in which chloride ions penetrate concrete are through hydrostatic pressure, capillary action, and diffusion. The least common method of chloride ion penetration is through hydrostatic pressure which occurs when water, containing chloride ions, is drawn into the concrete from differing pressures inside versus outside of the concrete. A constant hydraulic head such as this is very unlikely on actual concrete structures such as bridge decks, so it is usually of little concern. However, this mechanism could represent a major concern in marine environments. Another, more common, form of chloride attack in concrete is from capillary action. Concrete contains small void spaces that are referred to as capillaries which are essential to the ability of concrete to safely expand and contract during periods of freezing and thawing. However, during cycles of wetting and drying, water containing ions such as chloride can be drawn into these capillaries. When concrete becomes wet, surface tension forces draw water, containing chloride, into these capillary void spaces. Over the life span of the concrete, there is a net flow of water and ions into the concrete which can become a problem.

The most common chloride ion penetration mechanism is through diffusion which is the main concern when evaluating chloride ion penetration risk. Diffusion is driven by the presence of a concentration gradient and occurs from the movement of chloride ions from an area of high concentration to low concentration in an effort to reach constant, uniform concentration equilibrium. For bridge decks, this gradient mainly occurs as a result of the use of deicing salts

during winter months. Chloride ions, present in the solution of melted snow and dissolved salt, are diffused through the concrete deck surface.[1]

From the various methods described above, chemical ions, especially chloride ions, can penetrate and then attack the cementing materials in concrete to cause excessive degradation of the reinforcing steel and concrete itself. As ACI states, the penetration of chloride ions into concrete is "the major factor affecting the process of corrosion of embedded metals."[2] The chloride can oxidize and corrode the surface of the steel, thus degrading and shortening the life span of the imbedded steel significantly. In addition, this corrosion of the steel surface compromises the bond that exists between the concrete and steel reinforcement. As a result, the concrete can spall and separate from the steel reinforcement, frequently resulting in the rapid deterioration of bridge decks and leading to expensive repairs. The ingress of the chloride ions into concrete can also produce excessive cracking in the concrete itself. As the cracks form, the subsurface of the concrete becomes more exposed to the environment and, thus, more susceptible to further chloride ion penetration and further steel degradation and cracking.[3]

2.2 ASTM C1202: Rapid Chloride Ion Penetration (RCP) Test

The current test method specified by ASTM and AASHTO for the evaluation of the penetration of chloride ions in concrete is ASTM C1202 (AASHTO T277): "Standard Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration." [4] This test is more often referred to by its earlier name: "Rapid Chloride Ion Penetration Test" or more simply RCP test. This test does not actually directly measure chloride ion penetration, but rather the electrical conductance of concrete. Conductivity is the measure of the ability to conduct electrical current. So, the test measures the ability of concrete to conduct electrical current, an ability which has been proven to be correlated to chloride ion penetration. The test consists of a conditioning phase and a testing phase.

2.2.1 RCP Test Description

During the conditioning phase, the concrete samples are prepared so that any and all electrically conductive materials that are present in the samples are driven out. Concrete samples are cut from 4"x 8" cylinders into 2" thick specimens taken from the top of the cylinder. An impermeable coating is then applied to the side, curved part of the sample and allowed to dry. Once dry, the sample is placed into a vacuum apparatus where a constant vacuum is maintained for three full hours to drive out air which is trapped within the specimens. Figure 1 shows a typical vacuum apparatus setup.

Figure 1: RCP Test – Conditioning Phase

Meanwhile, water is boiled in a pressure cooker to drive out ions present in the water to form what's referred to in the specification as "deionized" water. After the initial 3-hour vacuum period, the deionized water is added and the vacuum left to continue for another hour. During this time, the deionized water is driven into the specimens to fill the voids where air was previously and to provide electrically neutral material for the testing phase. After this four hour period in the vacuum, the specimens are left in the water for a period of 18 hours to further incorporate the deionized water into the specimens. At this time, the specimens are free of any ions that might have been in the water or air in the concrete. This is important since the RCP test is evaluating the electrical current passed through the concrete specimens and should not be affected by anything else but the actual concrete. After this 18 hour period, the specimen is sealed into a voltage cell block with an impermeable plastic based sealant and allowed ample time to dry. The two sides of the voltage test block consist of a screen and reservoir system that can immerse the two specimen ends in solutions. Once the sealant is dried, the specimen is ready for testing.

During the testing phase, a voltage of 60 V is maintained across the ends of the specimen. One side of the test block is filled with a sodium chloride (NaCl) solution to immerse that end of the specimen. Likewise, the other end of the test block is filled with a sodium hydroxide (NaOH) solution to immerse that end of the specimen. Now, the two ends of the specimen have opposing charges and a constant voltage is applied across the concrete specimen. The current measurements are then integrated over the entire 6-hour period of the test to obtain the total charge passed in coulombs. Figure 2, adopted from ASTM C1202[4], shows this testing phase in detail.

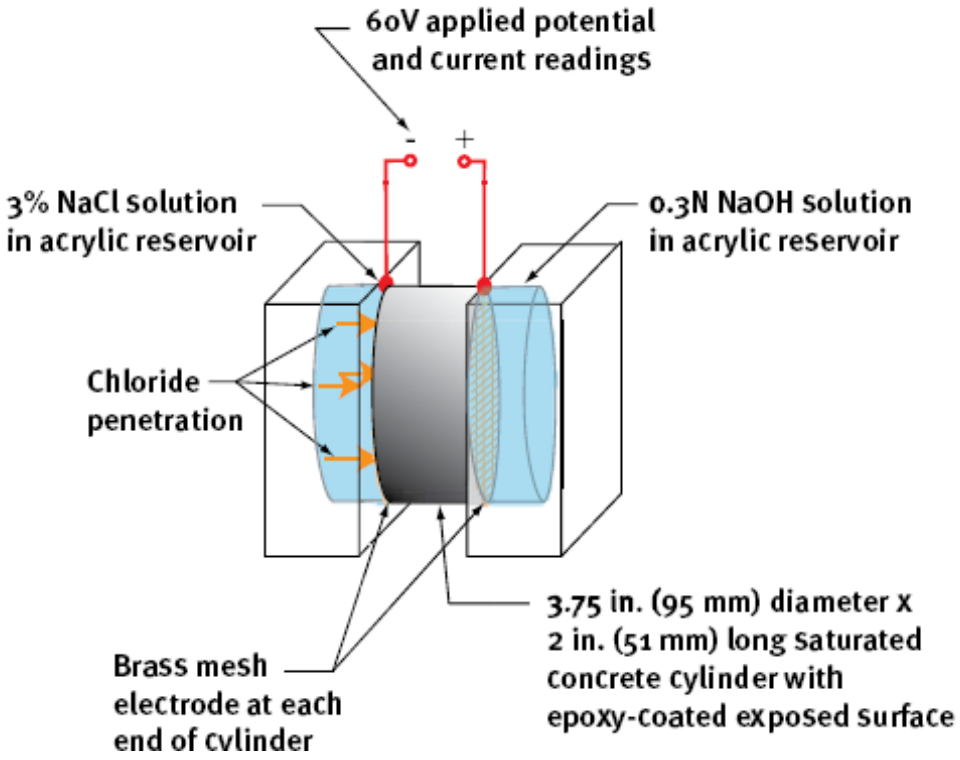

Figure 2: RCP Test – Testing Phase

As mentioned earlier, this total charge passed has been found to be related to the resistance of the specimen to chloride ion penetration; thus it is used as an electrical indicator of chloride ion penetration. The qualitative evaluation of chloride ion penetration of the concrete can be made using the delineations shown in Table 1, adopted from the ASTM C1202 specification. As discussed earlier, time and curing conditions are important variables, so ASTM specifies that when using the test for quality control and acceptance testing, "it is imperative that the curing procedures and the age at time of testing be clearly specified." [4] Thus, qualitative evaluations made using this table are only for the concrete at that specific age of testing and curing condition, not any future or previous evaluation of the concrete or of concrete cured in different conditions.

Table 1: Chloride Ion Penetrability Based on Charge Passed [4]

Charge Passed (coulombs)	Chloride Ion Penetrability
> 4,000	High
2,000 – 4,000	Moderate
1,000 – 2,000	Low
100 – 1,000	Very Low
< 100	Negligible

2.2.2 RCP Test Criticisms

Despite its widespread use and acceptance as a standard specification, there is much controversy in using the RCP test as detailed above as an evaluation of the penetration of chloride ions and the overall permeability of concrete. [3, 5-7]

One criticism of the RCP test is that chloride ion penetration is commonly used interchangeably with "permeability". The RCP test, by definition, is an indirect electrical indicator of the ability of concrete to resist chloride ion penetration. However, much of the time, the RCP test is used as a measure of the general "permeability" of concrete. Permeability implies the movement of any material through the concrete but usually pertains to water and ions, whereas chloride ion penetration is obviously just the measurement of chloride ions passing through the concrete.

The major criticisms of using the RCP test center around the use of supplementary cementitious materials (SCMs). The older, conventional method for determining the penetration of chloride ions into concrete is the ponding test, ASTM C1543[8], which is a well-respected test. In this test, sodium chloride solution is ponded on the surface of a concrete specimen for a period of 90 days, and samples from varying depths of the specimen are periodically analyzed for chloride content. The RCP test was developed to correlate well with the ponding test so it could be used as an alternative to the extensive testing period of the ponding test. However, many researchers

believe this correlation breaks down when concrete contains mineral admixtures or supplementary cementitious materials. [3, 5-7]

The general consensus is that transport of ions in concrete depends on the pore structure of the concrete, while the RCP test measures the electrical conductivity of the concrete which depends on both the pore structure of the concrete and the chemistry of the pore solution.[6] When SCMs are used, they can drastically change the chemistry of the pore solution which in turn can have a substantial impact on the RCP test results. However, the SCMs do not alter the concrete's pore structure, believed to be the true predictor of ion transport, to the extent of the change in RCP test results. In other words, the measured chloride ion penetration resistance of the concrete containing SCMs could be unrealistically high based on the RCP test, thus leading to a lower RCP test result. Some researchers, such as Shi[5] and Riding et. Al[7], seek to address this problem by suggesting the use of the RCP test only as a "quality control indicator when the concretes have the same components and mixing proportions."

Another criticism of using the RCP test when SCMs are present is that the concrete components might not be completely reacted within the normal 56 day period of testing. SCMs can often take a longer time to fully react compared to plain cement. As a result, adding SCMs to reduce chloride ion penetration risk, a proven method, might not actually reduce the RCP test results by the same degree. In this case, chloride ion penetration resistance of the concrete containing SCMs could be unrealistically low when measured with the RCP test.

One final criticism of the RCP test method arises from the heat generated by the samples during testing. Specimens typically heat up during the testing as a result of the current applied to the test blocks. This increase in temperature can then, in turn, increase the conductivity of the concrete and increase the RCP values measured. This does not usually present a problem with concrete that has low to moderate chloride ion penetrability, but does present a problem when low quality/highly permeable concrete is tested.[7] With increased conductivity comes increased temperature which can increase the conductivity even more, causing a cyclical effect. ASTM

C1202[4] addresses this potential problem by specifying a maximum temperature of 190°F in the test block solutions. If this maximum temperature is exceeded during testing, the test is to be terminated and samples identified as having "very high" chloride ion penetration. However, at any temperature it's clear that the conductivity is increased due to heat which tends to lead to excessive RCP values for more highly permeable concrete. In other words, the concrete might not be as permeable to chloride ions as indicated by the excessively high test values.

2.3 Factors Influencing Chloride Ion Penetration

A large amount of concrete research has been dedicated to evaluating and analyzing variables which affect chloride ion penetration. From this review of literature, it can be concluded that mix proportions, time, curing conditions, and the incorporation of supplementary cementing materials (SCM) are the main variables which affect chloride ion penetration.

2.3.1 Mix Proportions

Concrete is generally composed of water, cement, coarse aggregate, and fine aggregate. The relative proportion of these fundamental ingredients is responsible for essentially all the characteristics of the concrete including its resistance to chloride ion penetration. According to several researchers, the water-cement ratio is the biggest factor in mix design and proportioning which affects chloride ion penetration. It is well established that as water-cement ratio rises, chloride ion penetration rises. In other words, holding all else constant, concretes with lower water-cement ratios are more resistant to chloride ion penetration. [5, 9-12] Intuitively, this makes sense because the more water added to a mix for a given amount of cementitious material, the more porous the cement paste matrix. Not surprisingly, measuring chloride ion penetration is actually an effective method of identifying mixes that might have been altered with additional water on job sites. Several studies found that mixes which had been altered with additional water to restore slump right before placement had significantly lower chloride ion penetration resistance and, thus, higher RCP test values.[9]

Another variable, closely related to mix proportions and design, affecting chloride ion penetration is the composition of the aggregates. There is considerably less conclusive research conducted in this area, perhaps because of the difficulty of identifying the exact origins or properties of aggregates used in a given mix. However, in general, aggregates which are more porous in nature will typically allow more passage of water and chemical ions. Even though aggregate composition is said to affect chloride ion penetration, water-cement ratio is still established as the most important variable affecting chloride ion penetration in regards to mix design/proportioning.

The actual chemical makeup of the concrete materials is also an important factor in mix design. Specifically, the relative amounts of the compounds containing chloride which are present in the concrete are of interest. Many of the current regulations and guidelines for reducing corrosion risk from ACI deals with the percent of chloride by mass of the concrete mix. The main source of the chloride ion comes in the form of calcium chloride ($CaCl_2$).[13]

2.3.2 Time

The age of the concrete specimen is also a widely accepted variable affecting chloride ion penetration. As concrete ages, its resistance to chloride ion penetration increases so that its RCP test values decrease. Aging reduces the porosity of the capillaries in the concrete, thus inhibiting movement of chloride ions. The decrease in concrete's resistance to chloride ion penetration occurs mostly during the first two months after concrete placement when cement hydration, which causes this capillary reduction, is greatest.[9, 12] It is not surprising that there is a general trend of a faster decrease in chloride ion penetration during the first 28-56 days; the rate of decrease slows down by age 100 days and becomes about constant after that.[14]

It is worth mentioning that, after enough time, almost all concretes will reach an "acceptable" level of chloride ion penetration. However, if the level of penetration was not acceptable at earlier ages, the damage and corrosion associated with chloride attack could have already

resulted in unacceptable degradation of the concrete. Thus, while there is no specified age for the RCP test by ASTM or AASHTO, it is commonly accepted to conduct the test at 56 days or even 28 days if rapidly cured. The RCP test measures the chloride ion penetration risk of the concrete at the same age of the testing and doesn't necessarily allude to any earlier or later values of chloride ion penetration. Using 56 day measurements ensures a uniform comparison across the industry and ensures evaluation of the concrete at the appropriate time. For example, achieving low chloride ion penetration at an age of 2 years is meaningless if chloride ion penetration was high during its early age when much of the damage could have occurred. Abou-zeid et al. suggest that RCP values at 28 days to be 50-60% of those attained at 56 days. [10]

2.3.3 Curing Conditions

The curing conditions of concrete also affect the penetration of chloride ions. Across many studies, researchers have found that lab cured concrete samples will have significantly higher RCP values compared to field cured samples. Therefore, there is a general consensus that testing agencies must consider whether samples are lab or field cured and likewise must give careful attention to curing conditions when comparing test values from different mixes. The difference in RCP values may be in large part due to curing conditions instead of some other variable such as mix proportions.

Zhang et al.[15] further explored curing conditions by examining the role curing conditions play on various types of concretes containing supplementary cementing materials. It was concluded that, for a given water cement ratio, the chloride ion penetration of mixes that incorporated supplementary cementing materials (SCMs) such as fly ash were more affected by curing conditions than was normal concrete alone. The effect of supplementary cementing materials on chloride ion penetration is discussed later, but it is worth pointing out that curing conditions could have more of an impact on concrete mixes containing SCMs.

2.3.4 Supplementary Cementing Materials (SCM)

There has been extensive research studying the effect of adding supplementary cementing materials (SCMs) on chloride ion penetration. The three main SCMs that have been studied are also the most common in the field: fly ash, silica fume, and blast furnace slag. Researchers share an almost unanimous conclusion that all three of these SCMs improved chloride ion penetration in concrete and thus make the concrete more resistant to chloride ion penetration. [6, 14, 16-19]

It is believed that SCMs make concrete more resistant to chloride ion penetration by improving pore structure. SCMs are more dense than plain cement which results in a denser mix so that normally large pores are reduced in size resulting in what's called pore refinement. [6, 14] There is less chloride ion penetration with fewer and smaller voids. The pore refinement is thought to be most substantial with fly ash. Not surprisingly, researchers have found that fly ash increases the resistance of concrete to chloride ion penetration the most compared to other SCMs such as silica fume and blast furnace slag. [6, 14, 16-19]

2.4 Surface Resistivity

Despite their direct relation, the term resistance is commonly known and understood while resistivity is not as commonly understood. Resistance (R) is of course the opposition to passage of steady electric current and is defined as:

$$R = \frac{V}{I}$$

where V is voltage , I is current, and R has units of ohms.

Resistivity (ρ) is the "resistance of a cube of one unit in size" [20] (p.617) and is defined as:

$$\rho = R\frac{A}{L}$$

where R is resistance, A is area of the element, L is length of the element, and ρ has units of ohms - length.

The resistivity of concrete has long been a concern because of its relation to the risk of corrosion of reinforcing steel. As Polder [21] explains: concrete's ability to oppose an electric current, or resistivity, affects both the "initiation period (chloride penetration) and the propagation period (corrosion rate)" (p.125). However, up until the last 20-25 years, the methods for measuring resistivity required either embedded electrodes, which was invasive and required preplanning, or other methods which were usually too expensive. [20] In the 1980s, the surface resistivity techniques established in geotechnical soil analysis were applied to concrete which made the measurement of resistivity much more cost effective and non-destructive. This method consists of a hand held probe that is simply placed on the surface of the concrete surface to measure the resistivity.

A typical surface resistivity measuring probe consists of a hand held device with four electrodes, equally spaced apart, and connected to a measuring device. This four probe set-up is referred to as the Wenner probe. There is a constant current passed between the outer two electrodes, while the inner two electrodes measure the difference in current that can be attributed to the material, thus measuring the resistance and resistivity of the material.[22] Figure 3, adopted from Millard et al., shows the typical set up of a Wenner four-probe array.

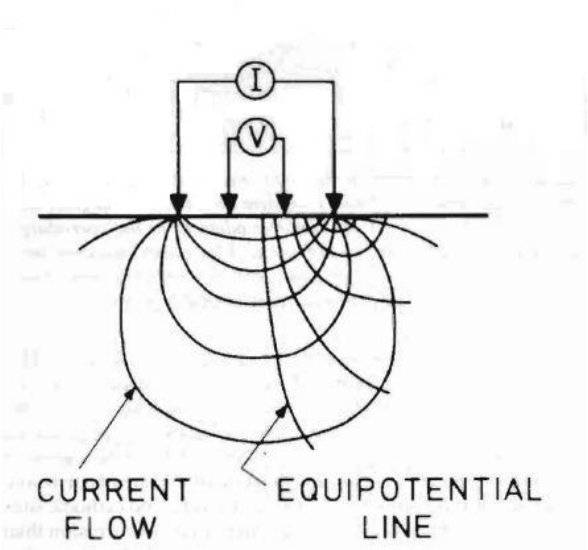

Figure 3: Wenner Four -probe Resistivity Setup [20]

As seen in figure 3, the current flow follows an arc pattern between the two outer probes, so the area per length term in the resistivity equation can be written as:

$$\frac{A}{L} = 2\pi a$$

where A is area and L is length as before, and a is the probe spacing.

The resistivity equation is then rewritten as:

$$\rho = 2\pi aR \text{ or } 2\pi a \frac{V}{I}$$

where R is resistance, V is voltage, and I is current as before.

Surface resistivity is currently used as a direct measure of the potential risk and rate of corrosion of embedded steel in reinforced concrete. The general limits of corrosion risk are well established from the research of Millard [22] and Figg and Marsden [23] and are included in the documentation of the surface resistivity meter used on this project. Table 2, adopted from Millard and Figg et al., shows the qualitative determination of corrosion risk of embedded steel at various ranges of resistivity.

Table 2: Surface Resistivity Thresholds (Semi-infinite Surface) [22]

Resistivity (kohms-cm)	Probable Corrosion Rate
< 5	Very High
5 - 10	High
10 – 20	Moderate / Low
> 20	Low

2.5 Surface Resistivity (SR) Test Method

As discussed in the previous section, SR is most commonly used as a measurement of corrosion risk in which a probe is placed onto a semi-infinite surface and measurements are compared to the established delineations of Table 2. On the other hand, SR measurements are relatively new in the context of evaluating chloride ion penetration and permeability. Thus, there is no official surface resistivity test method specified by ASTM or AASHTO for the evaluation of chloride ion penetration and permeability. However, there is a commonly accepted method that was developed from the research of Kessler et al. and the Florida Department of Transportation.[24] The state of Florida has since made this a standard test method designated as "FM 5-578: Florida Method of Test for Concrete Resistivity as an Electrical Indicator of its Permeability." [25]

2.5.1 SR Test Description

The SR test, as specified by FDOT, uses a surface resistivity meter configured in the Wenner four-probe spacing as detailed in section 2.4 to measure the surface resistivity of 4" x 8" concrete cylinders. First, marks are made around the circumference of the top face at the 0, 90, 180, and 270 degree points of the cylinder. Then the four-probe SR meter is placed on the longitudinal surface of the concrete at the 0 degree point ensuring that all four probes are in contact with the concrete surface, and the resistivity measurement is recorded. This process is repeated seven more times until eight measurements are completed, two at each degree mark. This process can be seen in figure 4.

Figure 4: SR Test Method

The average of these eight measurements is then computed and used to evaluate the permeability of the concrete using Table 3 adopted from the FM 5-578 specification and Kessler et al.

Table 3: Chloride Ion Penetration Based on Surface Resistivity (4" x 8" Cylinder) [24-25]

Chloride Ion Penetration	Surface Resistivity Test (kohm-cm)
High	<12
Moderate	12 - 21
Low	21 – 37
Very Low	37 – 254
Negligible	> 254

2.5.2 SR Test Advantages and Criticisms

It is rather easy to see the attractiveness of using this test method. The method is extremely fast, easy to learn, repeatable, and, most importantly, non-destructive. Not surprisingly, there are several researchers, DOTs, and organizations that want to implement the SR test method as an alternative to the RCP test method.

There are, however, some issues with using surface resistivity techniques which must be addressed in order to produce usable, reliable results. First, concrete is a non-homogeneous material and is likewise electrically non-uniform as well. Thus, measurements taken on one part of a sample will likely differ slightly from another part of a sample. The SR method described above addresses this problem by taking the average of eight measurements taken around the circumference of the cylinder sample. Second, proper surface contact is imperative to reliable SR readings. As a result, the surface should be measured as soon as possible after removing the specimen from curing before surface drying can occur. Proper surface contact is imperative to make sure the readings are only influenced by the sample and not affected by varying degrees of moisture. In other words, the electrically neutral wooden tips have to remain moist as does the surface of the concrete. When multiple measurements are conducted on several samples, the meter probes must be frequently re-wetted between measurements. Third, resistivity depends on concrete sample size. A semi-infinite slab sample and a 4” x 8” cylinder sample of the exact same concrete will have substantial differences in SR measurements that are due to size of sample and not actual resistivity differences. For instance, Table 2 shows SR thresholds for infinite and semi-infinite slab measurements which cannot be compared directly with values in Table 3 which shows SR thresholds for 4”x8” cylinder samples. The differences in section geometry, depth of specimen, and edge effects all contribute to these differences. [22, 23] Despite these criticisms of SR, it can still be a very quick, easy, and effective measurement tool as long as these potential pitfalls are addressed, and testing is done in a consistent manner for all samples.

2.6 RCP and SR Test Relationship

Because surface resistivity measurements are yet to be developed into a standardized specification as an indicator of chloride ion penetration, there is considerably less research literature about the factors which affect surface resistivity of concrete compared to the RCP test method. However, the conclusions of the existing research indicate that surface resistivity is affected by the same factors which affect the RCP test and chloride ion penetration in general: mix proportions, time, curing conditions, and the incorporation of supplementary cementing materials (SCM). [3, 18, 26] Both test methods share the same influencing factors because they are inherently related.

As explained in section 2.2, the RCP test does not directly measure chloride ion penetration but rather the electrical conductance of concrete which has been found to be an electrical indicator of resistance of concrete to chloride ion penetration. Conductivity (σ) is the measure of the ability to conduct electrical current. On the other hand, the SR test method measures resistivity (ρ) which is the opposition of electric current to flow. These two measurements are inherently related in that conductivity is actually defined as the inverse of resistivity as follows:

$$\sigma = \frac{1}{\rho}$$

where σ is conductance and ρ is resistivity

Thus, as Riding et al.[18] explains, the RCP test is essentially a "long-duration resistivity test" (p.390); or perhaps one could call it the inverse of a long-duration resistivity test.

Given the fact that SR and RCP testing have the same influencing factors as well as the fact that they are inherently related by definition, it is not surprising that several researchers have proposed the SR test method as a viable alternative to the RCP test to assess the chloride ion penetration of concrete. In fact, the FDOT SR test method [25], as outlined in section 2.5.1, is in the process of being reviewed and implemented into an accepted AASHTO specification as a standard test method for an electrical indicator of concrete's ability to resist chloride ion

penetration. In the research of Kessler et al. [24], from which the FDOT SR test method evolved, chloride ion penetration was classified for various types of SR sample test sizes as shown in Table 4. This table identifies the chloride ion penetration of concrete based on SR testing at 28 days for various sizes of concrete samples. The table also emphasizes the difference in SR testing that occurs due to sample size and the importance of not directly comparing SR test values for different sized samples.

Table 4: Chloride Ion Penetration Classification, SR vs. RCP Test [24]

Chloride Ion Penetration	**RCP test Charge Passed (coulombs)**	**28 Day Surface Resistivity Test**		
		4" x 8" Cylinder (kohm – cm) (a = 1.5")	**6" x 12" Cylinder (kohm – cm) (a = 1.5")**	**Semi-Infinite Slab**
High	> 4,000	< 12	< 9.5	< 6.7
Moderate	2,000 – 4,000	12 - 21	9.5 – 16.5	6.7 – 11.7
Low	1,000 – 2,000	21 - 37	16.5 – 29	11.7 – 20.6
Very Low	100 – 1,000	37 - 254	29 – 199	20.6 – 141.1
Negligible	< 100	> 254	> 199	> 141.1

3 Test Procedure

The purpose of this chapter is to describe the procedures used for collecting, transporting, and testing the concrete samples using both the RCP test and SR test.

3.1 Sample Collection and Transport

At concrete bridge deck pours across the state of Tennessee from February 2010 to the present, 13 extra 4"x 8" cylinders were cast by TDOT personnel specifically for use on this project. Of the thirteen cylinders for each deck pour, six cylinders were used to conduct compressive strength testing, three at 7 days and three at 28 days. Six cylinders were used for the actual RCP and SR testing, three at 28 days and three at 56 days. The remaining cylinder was used as an extra in case another sample in the batch was compromised or damaged. This extra sample was also used to measure SR values at 91 days to assess long-term SR variation.

Large marine coolers, outfitted with dense Styrofoam holders, were used to transport the set of 13 cylinders from each bridge pour. The cylinders were initially cast and cured as outlined in ASTM C31[27] for a period of at least 48 hours before transport. The coolers were then transported to TDOT Regional Headquarters in Nashville and then to the TDOT Region 1 office in Knoxville as soon as was possible by TDOT personnel. For pours conducted in Region 1, the transportation to headquarters was skipped. Once at the Region 1 office in Knoxville, the coolers were picked up and brought to the University of Tennessee campus where they were immediately immersed in a lime tank bath per ASTM C511[28] as shown in figure 5.

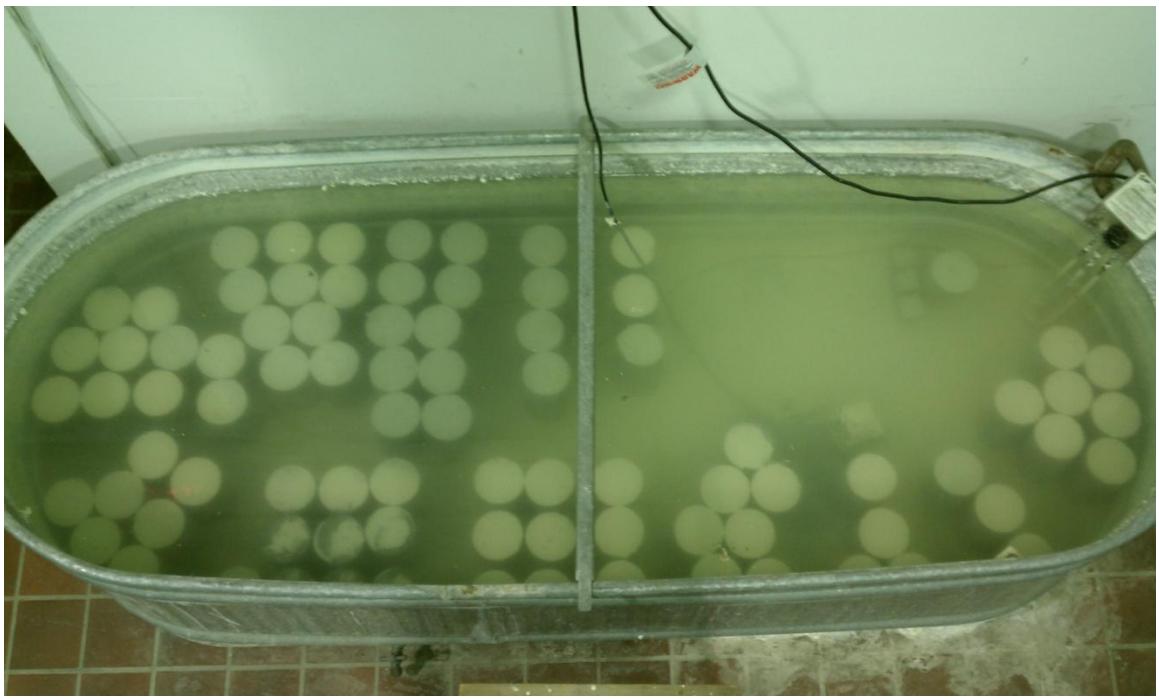

Figure 5: Lime Water Curing Tank

Due to the large geographic area for potential samples, the time period for the samples in the coolers varied but usually ranged between 7 and 21 days. During this time, the concrete cylinders were kept in a relatively controlled environment inside the cooler which was placed in moisture room per ASTM C511[28], at one of the TDOT regional offices. The caps remained on the cylinders during this whole process. Once at the University of Tennessee campus, the caps were removed, forms were stripped, and the samples were placed in the lime tank bath.

3.2 Sample Testing

As mentioned above, the collection, transport, and testing procedures varied somewhat depending on the origin of the samples and location of the deck pour. Seven day compressive strength tests were done at UT for samples that were received within a week after pour. This was typically only possible for Region 1 samples. For regions other than Region 1, 7-day compressive strength tests were done at the other region offices before transport to Region 1.

Twenty-eight day compressive strength tests were then conducted at the UT campus for all samples. All compressive strength tests were conducted in accordance with ASTM C39.[29] Both chloride ion penetration tests (RCP) and surface resistivity tests (SR) were conducted at 28 and 56 days as described in section 2.2 and 2.6 of this thesis, respectively. Each sample was tested using the SR test meter first and then cut into proper sizing and prepped for the RCP test. Thus, only 3 samples were used at 28 days and another 3 samples were used at 56 days for RCP and SR testing combined. The average RCP and SR values of the 3 samples were then recorded. In addition, SR measurements were taken at 28, 56, and 91 days on the "extra" thirteenth cylinder to observe long term variation in SR values.

4 Results

The purpose of this chapter is to present the data and findings of the research project. Through May 18th, 2011, 54 sets of cylinders had been received: 9 from Region 1, 19 from Region 2, 6 from Region 3, and 20 from Region 4. The collected data can be seen in Tables 5 and 6.

Table 5: Collected Data

Pour Information				Surface Resistivity (kohm-cm)			Rapid Chloride Ion Penetration (coulombs)	
Pour Date	**Region**	**County**	**28 day f'c (psi)**	**28 day SR**	**56 day SR**	**(28/56) Ratio**	**28 day RCP**	**56 day RCP**
2/22/2010	4	Carroll	6239	8.9	15.7	0.56	7770	2670
3/13/2010	4	Henderson	5570	9.6	19.0	0.50	5084	2645
3/15/2010	2	Hamilton	5488	7.3	10.1	0.72	6993	5850
3/16/2010	1	Cocke	5351	11.5	19.1	0.60	3912	2135
3/17/2010	1	Knox	6737	13.1	23.4	0.56	2645	1537
3/30/2010	2	Hamilton	5096	10.4	11.8	0.88	5862	4896
4/6/2010	1	Carter	5358	12.1	17.4	0.70	5157	3543
4/22/2010	1	Blount	5576	16.2	28.6	0.57	2351	1209
5/3/2010	1	Knox	4230	14.1	24.3	0.58	3697	2570
5/25/2010	4	Haywood	4249 (14day)	10.9	19.3	0.56	9652	3724
6/9/2010	2	Coffee	4653	8.1	11.0	0.74	9713	4935
6/10/2010	2	Clay	6740	19.1	24.5	0.78	3127	1969
6/23/2010	1	Union	4840	13.5	22.4	0.60	4156	2410
7/2/2010	3	Williamson	3604	11.4	17.6	0.65	5132	2821
7/2/2010 (2)	2	Polk	5610	11.2	15.6	0.72	5921	4334
7/6/2010	3	Davidson	3743	12.4	17.0	0.73	4062	3480
7/8/2010	4	Madison	7627	N/A	7.2	0.00	N/A	7536
7/15/2010	4	McNairy	4729	5.8	6.2	0.94	14197	12279

Table 5. Continued

Pour Information				Surface Resistivity (kohm-cm)			Rapid Chloride Ion Penetration (coulombs)	
Pour Date	**Region**	**County**	**28 day f'c (psi)**	**28 day SR**	**56 day SR**	**(28/56) Ratio**	**28 day RCP**	**56 day RCP**
7/27/2010	4	Madison	4305 (14day)	11.7	18.9	0.62	5879	2592
8/10/2010	3	Davidson	4155	11.7	19.2	0.61	5359	2423
8/14/2010	4	Henderson	4117	8.4	13.8	0.61	9441	N/A
8/19/2010	4	McNairy	4898	6.4	7.4	0.86	Maxed Out	Maxed Out
9/1/2010	4	Lake	4393	11.6	21.4	0.54	4036	1868
9/3/2010	1	Sevier	6483	18.6	31.5	0.59	2402	956
9/8/2010	4	Gibson	4751	12.9	25.5	0.51	3265	1614
9/11/2010	2	Hamilton	3835	13.1	27.4	0.48	3372	1567
9/14/2010	1	Sevier	6076	18.1	35.4	0.51	2383	921
9/21/2010	3	Davidson	4887	10.2	13.9	0.73	3985	2751
9/28/2010	2	Warren	4884	11.7	19.8	0.59	4138	1987
10/5/2010	2	Warren	5114	14.1	20.7	0.68	2799	1667
10/12/2010	2	Warren	5219	12.5	23.1	0.54	4350	1622
10/14/2010	2	Warren	4765	9.4	18.3	0.51	5127	1919
10/21/2010	3	Williamson	5125	12.7	23.0	0.55	3857	2096
10/27/2010	3	Montgomery	8948	22.2	37.4	0.59	1317	851
11/2/2010	4	Decatur	4101	8.0	18.4	0.43	Maxed Out	2538
11/4/2010	4	Shelby	9018	14.1	23.6	0.60	N/A	1623

Table 5. Continued

Pour Information				Surface Resistivity (kohm-cm)			Rapid Chloride Ion Penetration (coulombs)	
Pour Date	**Region**	**County**	**28 day f'c (psi)**	**28 day SR**	**56 day SR**	**(28/56) Ratio**	**28 day RCP**	**56 day RCP**
11/192010	4	Haywood	5260	9.3	17.6	0.53	N/A	2981
12/22/2010	2	McMinn	5891	11.3	13.7	0.82	6299	4273
1/4/2011	4	Naywood	4443	9.9	16.2	0.61	5808	2582
1/19/2011	4	Gibson	5272	8.7	N/A	N/A	6546	N/A
1/28/2011	2	Polk	6131	14.2	13.7	1.04	3486	3396
1/28/2011 (2)	2	Warren	4547	15.1	22.5	0.67	3306	1580
1/29/2011	2	Warren	5728	14.2	31.1	0.46	3071	1298
2/22/2011	2	Marion	4650	7.1	6.8	1.04	Maxed Out	Maxed Out
3/4/2011	1	Knox	6547	12.0	13.1	0.92	3918	3138
3/9/2011	4	Crockett	5203	14.4	30.0	0.48	3522	1298
3/11/2011	4	Dyer	6799	7.6	14.9	0.51	Maxed Out	2440
3/15/2011	4	McNairy	6557	5.5	6.6	0.83	Maxed Out	Maxed Out

Table 6: Data Summary

Pour Information			Surface Resistivity (kohm-cm)			Rapid Chloride Ion Penetration (coulombs)	
Region	**Samples**	**Avg. f'c (psi)**	**Avg. SR (28)**	**Avg. SR (56)**	**Avg. (28/56) SR Ratio**	**Avg. RCP (28)**	**Avg. RCP (56)**
Region 1	9	5689	14.4	23.9	0.62	3402	2047
Region 2	19	5314	11.7	17.9	0.72	4718	2940
Region 3	6	5077	13.4	21.4	0.64	3952	2404
Region 4	20	5325	9.6	17.1	0.58	6116	2778
Total or Average	**54**	**5351**	**12.3**	**20.1**	**0.643**	**4547**	**2542**

5 Evaluation of Results

The purpose of this chapter is to interpret, evaluate, and discuss the data and findings of the research project.

5.1 Data Interpretation

As shown in Table 5, there were a few instances where testing was not possible as noted by "N/A" which stands for "Not Available." The reasons these tests were not run varied, but were mainly due to transportation difficulties or scheduling conflicts with the lab facility. In other words the samples were not received by the testing date or the lab facility at the University of Tennessee was unavailable due to the holidays or closed due to athletic events held in Neyland Stadium which is next door to the building housing the testing laboratory.

There are also several distinctions of "Maxed Out" in Table 5. This term was used to classify two special cases of sample testing. The first reason was due to the temperature in the test blocks becoming excessively high, or "Maxed Out." As discussed in section 2.2.2, temperature effects on RCP testing can be significant with highly permeable concrete and can result in invalid tests. So, in this case, "Maxed Out" referred to tests that were stopped because of risk of damage or leaking of the test blocks and/or excessive temperatures as defined in ASTM C1202.[17]

Another reason for the "Maxed Out" distinction was because the capacity of the testing machine was exceeded, or the machine "Maxed Out." The RCP testing machine records current passed at each 30 minute interval for the whole 6 hour period. From these data a plot of current versus time can be plotted and then the area underneath the curve integrated to obtain charge passed, in coulombs, during the 6 hour period. The testing machine has a capacity of measuring a maximum current, I, of 999 amperes. Once this maximum is reached, the testing machine performs integration for the rest of the 6 hour period using the 999 amperes, but the actual

current would likely keep rising past the 999 ampere value. This appears to be a safety feature of the RCP testing machine to keep a potentially hazardous current from building up in the test blocks and the machine itself. It's worth pointing out that these "Maxed Out" samples correspond to low SR values. In either case, the samples are to be regarded as "high" chloride ion penetration according to ASTM C1202.[17] There is no quantitative number that can be assigned to these samples; therefore, the samples are not included in the correlation graphs. However, it is still important to distinguish these samples because they represent samples that have obviously high chloride ion penetration risk. One of the reasons the SR test is attractive as an alternative to RCP testing is that it does not have this temperature variation which alters resulting measurements.

5.2 Surface Resistivity and Rapid Chloride Ion Penetration Test Correlation

5.2.1 Statistical Analysis

The main thrust of this research project was to evaluate and identify the correlation of SR and RCP test methods for the Tennessee Department of Transportation. Figures 6, 7, and 8 show the various relationships between SR and RCP for the collected data. The RCP test is the accepted method of measuring chloride ion penetration, so it represents the independent variable, while SR is the dependent variable.

Figure 6 shows the relationship of SR vs. RCP regardless of age. As the project progressed, the correlation of SR and RCP was found to exist regardless of the age of the specimen at testing. In other words, at any given RCP value, there is a corresponding SR value whether the sample is tested at 28 or 56 days. As seen on the graph, the correlation of 0.89 is strong; it is believed that much of the remaining unexplained variability is likely due to the inherent variability of a non-homogeneous material such as concrete.

Figure 7 shows the correlation of SR at 56-days and RCP at 56-days which has an R^2 value of 0.89, again indicating a strong correlation.

Figure 8 shows the relationship of SR at 28-days vs. SR at 56-days. This information is needed because any performance criterion would need to be based on a 28-day measurement. Thus, correlating a 56-day RCP value to a 56-day SR value, then proportioning that value to a 28-day SR value appears to be the most promising approach. As seen in Figure 8, the linear relationship shows that 56-day SR values are roughly 60% of the 28-day SR measurements. The R^2 value of 0.59 is rather low and only represents a moderate correlation. However, this ratio is similar to other research studies such as Abou-zeid et al.[5] who concluded that 56-day values can be assumed to be 50-60% of the 28-day values. With more data during the next cycle of the project, this relationship will be further explored and refined, but it is expected to stay around 55-65%.

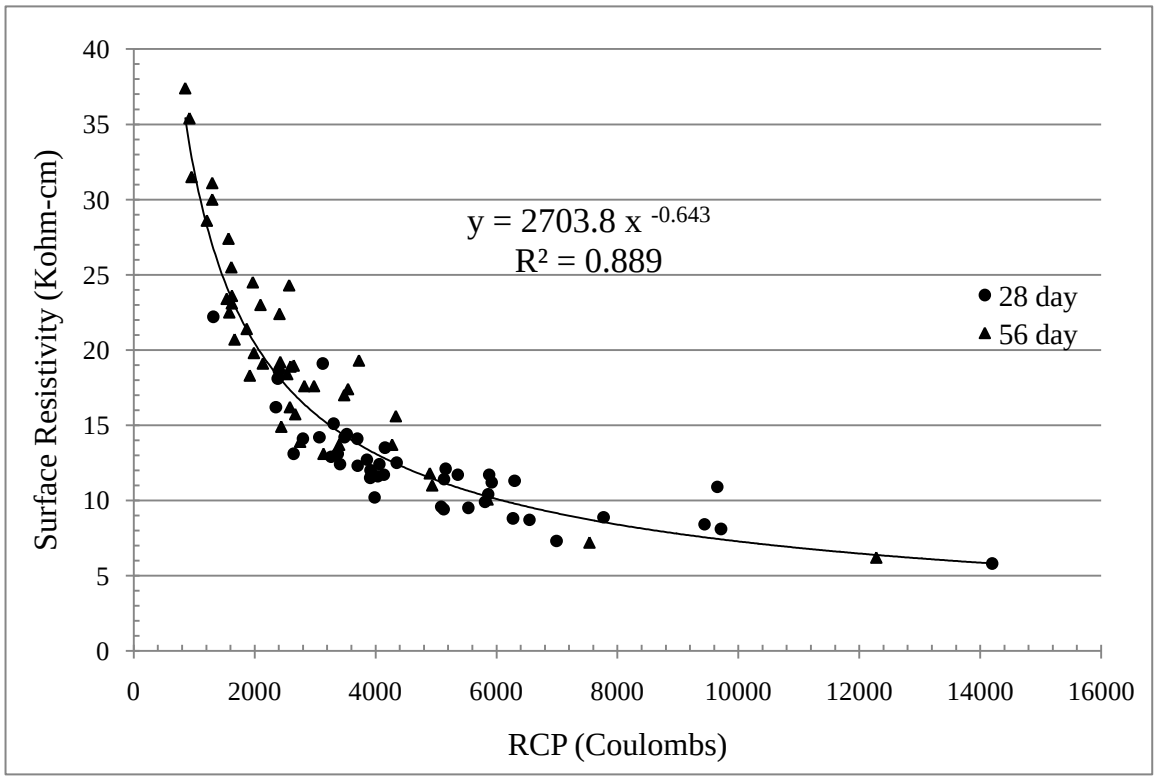

Figure 6: SR vs. RCP (Combined 28 and 56 Day Data)

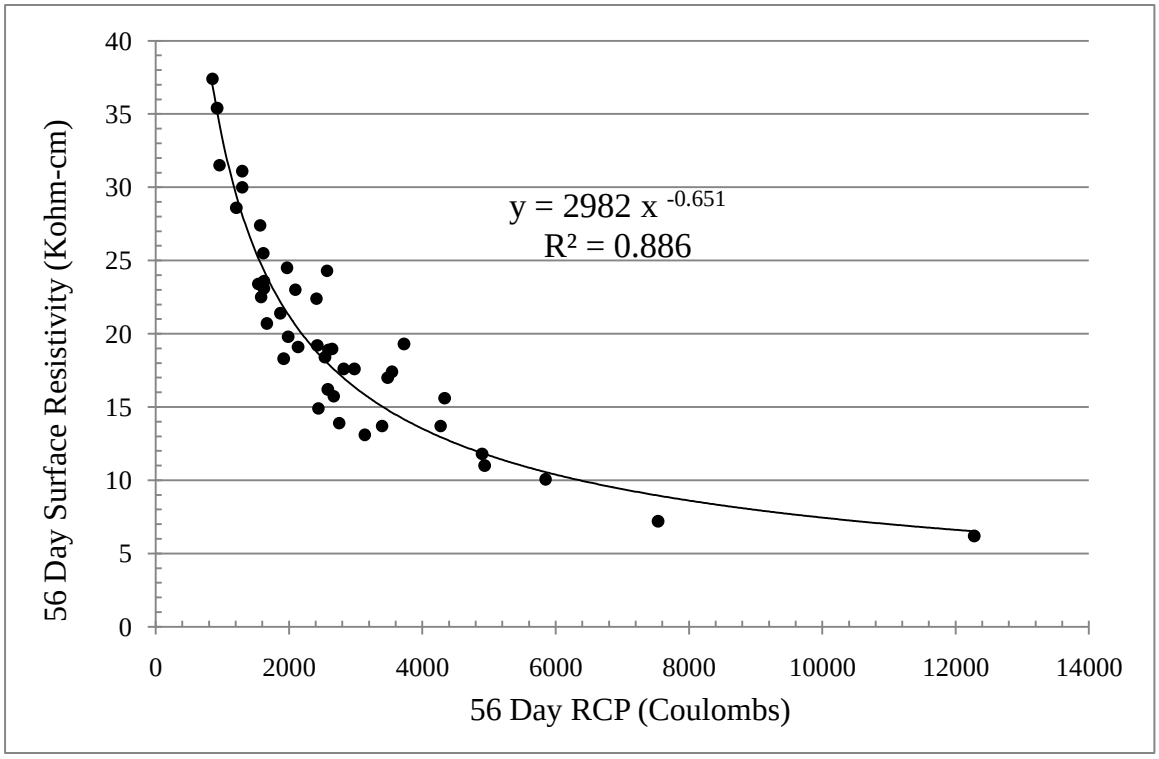

Figure 7: SR (56 Day) vs. RCP (56 Day)

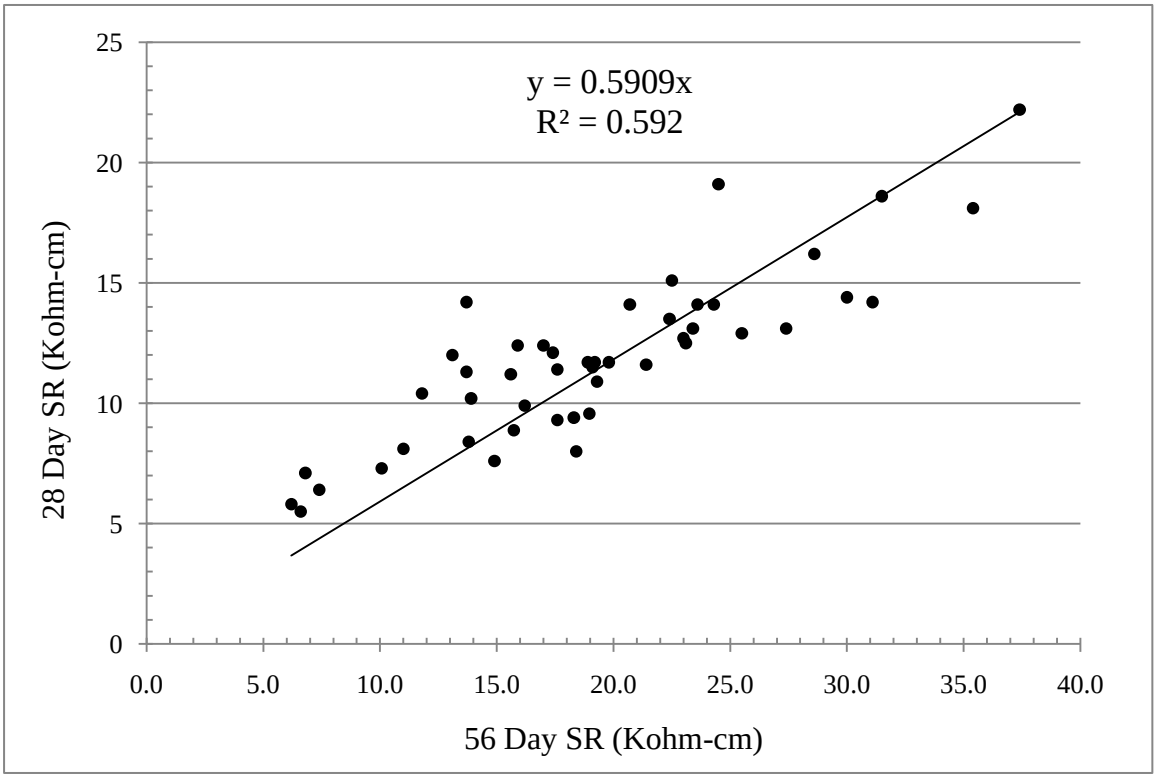

Figure 8: SR (28 Day) vs. SR (56 Day)

It is worth pointing out that all the correlations were improved (higher R^2 value) or stayed constant as the research progressed. This trend indicates that with continued samples and data, the correlations will continue to improve and give more confidence to the correlation equation.

The power regression model, of the form $y = ax^b$, was used to relate SR at 56 days to RCP at 56 days. Intuitively, this model makes sense when a curved, inverse relationship is evident. It has also been used on several other major research projects where RCP vs. SR correlations have been made.[3, 24, 26] Also, a power model is an intrinsically linear model wherein, by transformation, it can be reduced to a linear model of the form $\log(y) = \log(a) + b\log(x)$. The linear model can then be evaluated using the common least squares linear regression to evaluate the "goodness of fit" of the model to the actual data. Typically the goodness of fit is determined by the coefficient of determination also known as the R^2 value. [30]

As shown in Figures 6 and 7, for the data reported herein, the sample coefficient of determination for the linear regression analysis, R^2, is 0.89 and continues to increase with further data. A coefficient of determination value can vary between 0 and 1, where a value of 0 would indicate a completely random set of points and no correlation between variables of interest, and a value of 1.0 would indicate that every data point lies directly on the line. The R^2 value of 0.89 indicates that 89% of the observed data variation is explained by the model and that only 11% is not strictly explained by the model. The term variance can be thought of as a typical or representative deviation from the sample mean within a sample – in this case the deviation of the data from the fitted regression line. Interpretation of the terms "statistical significance" and "strong correlation" is not generally obvious to non-statisticians. However, most textbooks and literature agree that a correlation is weak if $0 \leq R^2 \leq 0.5$, strong if $0.8 \leq R^2 \leq 1.0$, and moderate otherwise. So, the coefficient of determination of 0.89 for the data comparing RCP and SR values falls well within the strong correlation category.[30]

The intent of this research is to provide sufficient documentation such that this correlation can be used by TDOT as justification for minimum performance criteria in the definition of a

performance-based specification to be used for concrete in Tennessee bridge decks. To use this correlation, two determinations have to emerge from the research: (1) there has to be a statistically believable correlation between SR and chloride ion penetration, and (2) difficult decisions must be made regarding the appropriate permeability level, as indicated by an SR measurement, to specify for each of the four regions. The first goal of a statically believable correlation has been established in this research so far. In the next phase of this research, the confidence and refinement of this correlation will continue to grow as more data are collected. Substantial progress has been made toward achieving the second goal of a decision about the acceptable limits of RCP and SR test values to be used in a performance based specification and are discussed in section 5.4. The next cycle of this project, will focus more attention on actually deciding on and implementing a performance based specification.

5.2.2 Equation Comparison to Literature

As seen in Figure 7, the correlation equation obtained from this research is:

$$SR = 2982\ (RCP)^{-0.651} \text{ with } R^2 = 0.89$$

where SR is surface resistivity (kohm-cm) and RCP is the charge passed in the 6 hour RCP test (coulombs)

There are several similarities and differences between the correlation equation obtained in this research and that obtained in similar research projects from Kessler et al.[24] and Smith et al.[26] which act to support these research findings and point out the need for actually conducting this work.

The correlation equation obtained from the research of Kessler et al.[24] and used by FDOT is

$$SR = 5801.2\ (RCP)^{-0.819} \text{ with } R^2 = 0.95$$

The correlation equation obtained from the research of Smith et al.[26] is

$$SR = 16573\ (RCP)^{-0.813} \text{ with } R^2 = 0.89$$

Because these equations are power regression models, it is rather difficult to make comparisons simply by looking at the equations and comparing numbers. Therefore, a graphical comparison is more useful and can be seen in Figure 9.

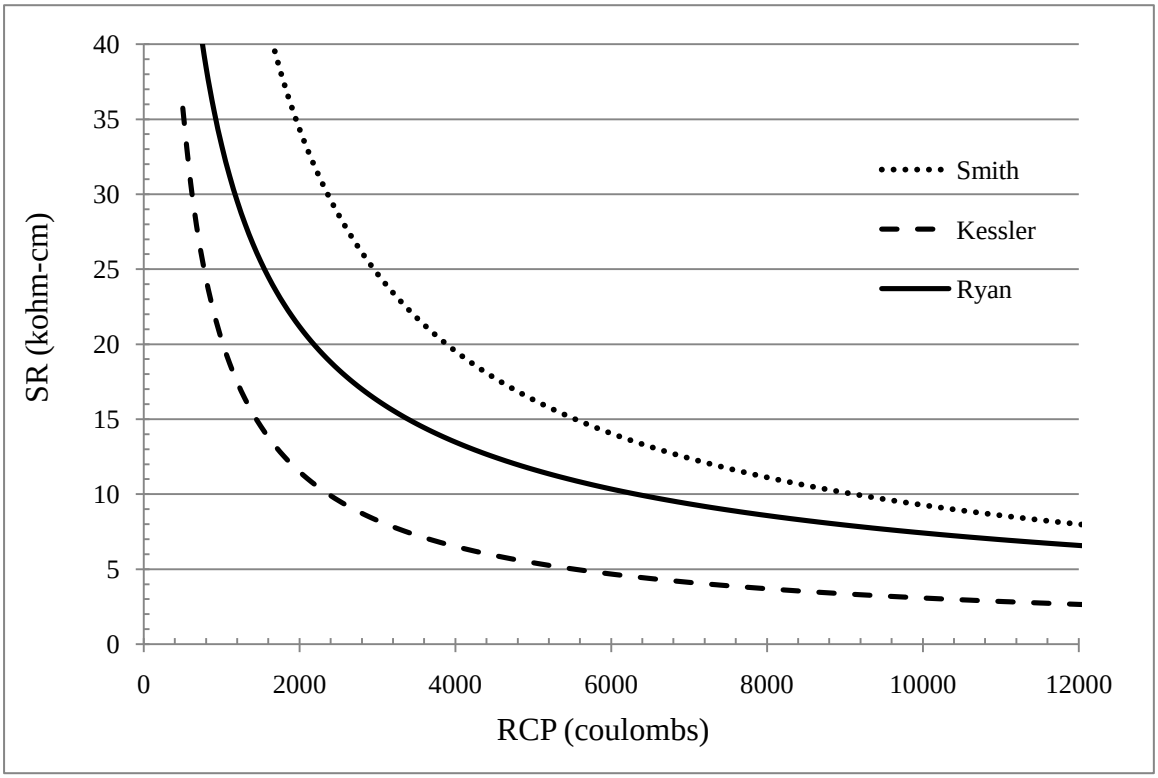

Figure 9: Correlation Equation Comparison with Literature

Two conclusions can be reached from comparing these equations and graphs. First, all three research projects have similarly shaped inverse curve relationships, a fact which reflects the consistency of the inherent relationship between surface resistivity and the RCP test. Second, while their general shapes are similar, there is quite a bit of discrepancy between the actual equation curves. At first thought, it might seem that all three of these projects should yield the exact same correlation equation. However, upon further analysis it is not surprising that these correlation equations are quite different. The materials used for each project originated from

different locations and thus have a very different composition. The resulting equations reflect the differences in aggregates that exist between the concrete materials used. The substantial difference in the correlation equations also points out the need for actually conducting this research in the state of Tennessee with the concrete materials that TDOT actually uses for Class D bridge concrete. The correlation equation of Kessler et al.[24] from FDOT, for example, cannot directly be applied to concrete produced in Tennessee or other states. It should also be mentioned that the curing conditions for each research project were slightly different. For example, Kessler et al.[24] and Smith et al.[26] used similar moist room curing while this research project used submerged curing in a water tank – the likely method that will be used by TDOT if this type of testing were to be implemented.

5.2.3 Use of Correlation Equation

As discussed in section 5.2.1, correlating a 56-day RCP value to a 56-day SR value, then proportioning that value to a 28-day SR value, appears to be the most promising approach for finding a an appropriate 28-day SR measurement for use in quality control. To implement this procedure into a performance-based specification, an acceptable 56-day RCP value must first be agreed upon.

Ex: 2000 coulombs at 56 days

Next, the 56-day SR value is determined from the correlation equation and the 56-day RCP value

Ex: $SR_{56} = (2982)\ (2000^{-0.651}) = 21$ kohm-cm

Finally, that 56-day SR measurement can be proportioned to a 28-day SR measurement.

Ex: $SR_{28} = (0.60)\ (19) = 12$ kohm-cm

5.3 Regional Analysis and Comparison

One of the by-products of conducting this research was obtaining substantial quality control information for TDOT class D concrete mixes from across the entire state of Tennessee. The Tennessee Department of Transportation (TDOT) is broken up into 4 regions across the state. Regional comparisons were done to evaluate any major differences in quality control data, namely, compressive strength, RCP test values, and SR test values.

Figure 10 compares the average compressive strength of the concrete samples across each of the 4 regions. All samples included in the data were "Class D" mixes which have a 4000 psi compressive strength minimum design. One can see from Figure 10 that all four regions have compressive strength averages well over the 4000 psi specified minimum.
While there is a clear difference between the regions, especially between, for example, Region 1 and Region 3, it warrants little attention since the values are still well over the 4000 psi strength minimum, and the number of samples from Region 3 is too small to make a meaningful comparison.

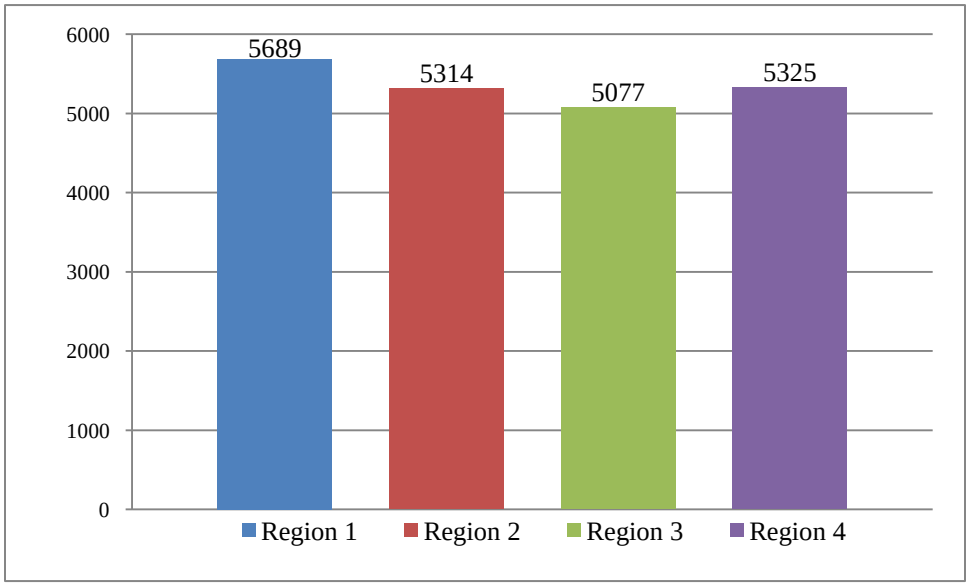

Figure 10: Average Regional f'c (psi)

Figures 11 and 12 compare the average RCP and SR test values, respectively, for the concrete samples from across each of the 4 regions. In general, when the regions are put in order of largest to smallest RCP, the same order is achieved by organizing the regions in order of smallest to largest SR. This trend reinforces the inverse relationship that is evident between SR and RCP as found in section 5.2.1.

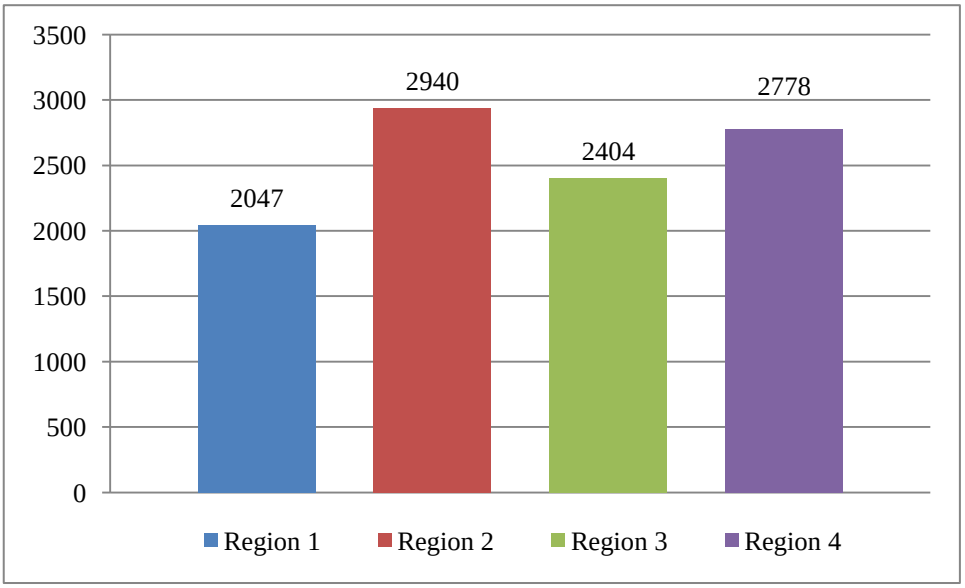

Figure 11: Average Regional 56 Day RCP (coulombs)

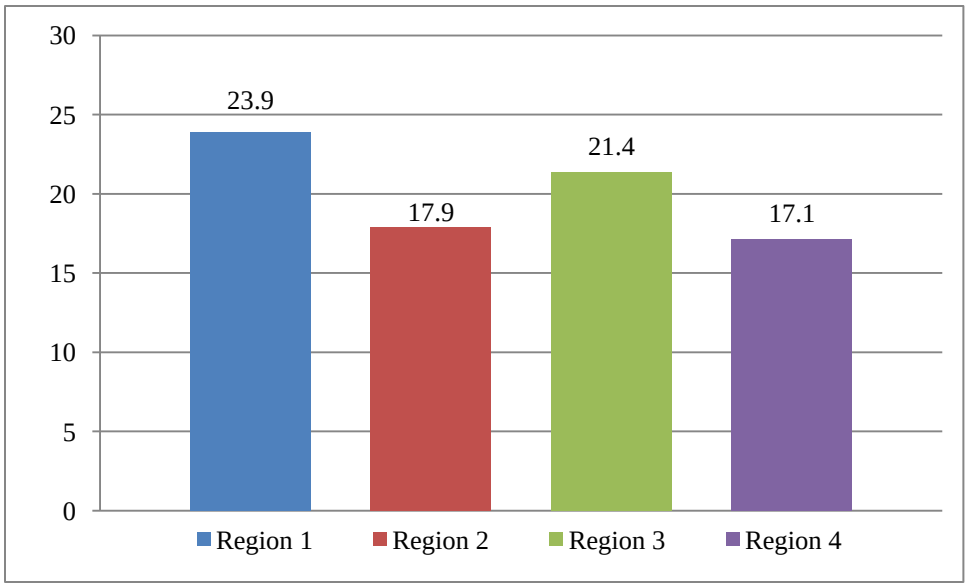

Figure 12: Average Regional 56 Day SR (kohm-cm)

The mix designs do not vary much, if at all, between samples and/or the various regions. They are all TDOT Class D concrete mixes and almost all contain fly ash. However, there clearly is a difference between the regions which gives rise to the different averages in quality control parameters, specifically SR and RCP. The differences in SR and RCP probably arise from differences in concrete materials such as fine and coarse aggregates. Producers across the state of Tennessee typically use materials which are readily available to them locally. Thus, differences in aggregates can be attributed to geological differences across the state of Tennessee from which the aggregates originate. Further research into the composition of the concrete materials across the regions will be conducted during the next cycle of the research to give better insight into what variables are responsible for changing chloride ion penetration as measured by RCP and SR testing.

From Figures 11 and 12, it is clear that Regions 2 and 4 seem to have similar 56-day values of around 3000 coulombs and 22 kohm-cm for RCP and SR, respectively, while Regions 1 and 3 have similar values around 2000-2400 coulombs and 17 for RCP and SR, respectively. As can be seen from Table 6, there is a substantial difference in sample size from Regions 1 and 3 compared to Regions 2 and 4. Therefore, at least some of this pairing of values between Regions 1 and 3 compared to Regions 2 and 4 might be simply due to difference in sample size. One goal of the next cycle of this research is to increase the number of samples from Regions 1 and 3 which currently have far fewer samples than Regions 2 and 4.

5.4 Chloride Ion Penetration Risk Classification for Collected Data

While the main purpose of this research was to analyze and evaluate the correlation between SR and RCP tests regardless of the actual values of either test measured, it is also useful to classify and evaluate the current chloride ion penetration risk of the concrete sampled from across the state of Tennessee.

Table 7 shows the number of samples in each level of chloride ion penetration risk as categorized by ASTM C1202[17] and Kessler et al.[24] and FDOT[25] by both RCP and SR testing. Over 60% of all samples tested were categorized as having moderate to high chloride ion penetration risk using RCP or SR values. Certainly at the "high" level and possibly the "moderate" level, significant damage can result in the concrete due to chloride ion propagation and the increase in corrosion risk as discussed in section 2.1. This situation represents a real challenge for TDOT in reducing bridge deck maintenance and repairs.

Table 7: Classification of Data by RCP and SR Tests[17, 24-25]

Chloride Ion Penetration	56 Day RCP	56 Day SR
High	10	8
Moderate	19	22
Low	14	16
Very Low	3	1
Negligible	0	0

The implementation of a performance-based specification having a minimum 28-day SR value would be directed toward eliminating much of the "moderate" and "high" risk concrete. Current thinking is that the risk of chloride ion penetration is too high across the state of Tennessee. A level of "low" risk would be beneficial to producing higher quality and longer lasting concrete which would require lower maintenance and repair costs in the long-term. A "low" risk level would correspond to a maximum of 2000 coulombs for RCP according to ASTM C1202.[17] Based on the correlation equation from section 5.2.3 developed in this research and a 60% 56-day to 28-day SR conversion, the resulting 28-day SR minimum would be 12 kohm-cm. Perhaps the best way to implement such a specification would be step-wise with a reduction of the minimum value occurring over the first couple years of its implementation. For example, in its first year, the specification could give a minimum SR value at 28 days of approximately 16 kohm-cm and then reduce that number by 2 kohm-cm over the next 2 years until the acceptable 12 kohm-cm value is eventually specified.

6 Conclusions

The implementation of a performance-based specification could potentially reduce maintenance costs and repairs for bridges by ensuring adequate durability of concrete. Chloride ion penetration represents an important concern when evaluating the durability of concrete and is impossible to predict with current prescriptive specifications. The currently specified method for the determination of chloride ion penetration in concrete, known as the Rapid Chloride Ion Penetration (RCP) test, is laborious, time consuming, somewhat user dependent, has a high coefficient of variation, and is widely criticized by researchers, making it unrealistic to specify in any performance-based specification. Therefore, a related test known as the surface resistivity test has been proposed as a viable alternative to evaluate chloride ion penetration risk and be used in a performance-based specification.

The evidence of the correlation and use of the SR test as an effective alternative to the RCP test in measuring chloride ion penetration risk is substantial based on this research and that conducted by others. Surface resistivity and conductance, as measured by the RCP test method, are inherently related, and the data are likewise supportive. In addition, the SR test method as presented here is a more appropriate test method to specify in a performance-based specification and is also not affected by temperature, so misleading results are not produced when highly permeable concrete is tested.

It is clear that SR is a suitable replacement to RCP, but as mentioned herein, RCP is not exactly the "gold standard" in chloride ion permeability. Thus, the SR test suffers some of the same drawbacks, mainly the uncertainty of its use when supplementary cementitious materials are present in concrete. The gold standard in chloride ion penetration assessment, if there is in fact a gold standard, would be the ponding test[19] which is even more laborious and time consuming than the RCP test, making it just as impractical as the RCP test for inclusion in a performance-based specification. The RCP test was designed to correlate well with the ponding test, but there was not much use of supplementary cementitious materials at that time. Therefore, there is a

lack of testing of supplementary cementitious materials with the ponding method which gives rise to this uncertainty around the RCP test and likewise the SR test. If the RCP test is the accepted method, and SR represents a sound, well researched alternative that is dramatically easier, faster, and has less variability than the RCP test, – why not use the SR test method? The SR test method gives the same, if not better, prediction of the chloride ion penetration risk of concrete.

The data thus far indicate that concrete from across the state of Tennessee typically has a moderate to high risk of chloride ion penetration. It would be beneficial to evaluate or inspect some of these bridges which were classified as having "high" chloride ion permeability and ones that were "low" to compare how they appear and behave long term. Also, keeping track of repair and/or damage expenses in the long term for the two types of bridges and comparing it to original SR/RCP data would be interesting and helpful. Implementing a performance based specification in Tennessee that outlines a minimum SR test value at 28 days would be expected to decrease the risk of chloride ion penetration and increase the quality of class D concrete and reduce maintenance and repair costs for bridges.

This research project will continue for another 2-year cycle where more samples will be collected to establish more confidence in the RCP versus SR correlation presented herein. In addition, this extension will allow for a much needed trial period to actually try out and refine a specification that would utilize the SR test measurements in a performance based specification.

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Vita

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